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In This Issue

Charles Stelzried and Michael Klein

In this issue's lead article about NASA's deep-space telecommunications road map, Chad Edwards, *et al*., write that with future faster and cheaper planetary missions, the coming decade promises a significant increase in the number of missions that will be simultaneously supported by NASA's Deep Space Network (DSN). Outer-planet missions, operating at great distances, and data-intensive orbiter (or *in situ*) missions incorporating high-bandwidth science instruments will require improved telecommunications capabilities. The Tele-communications and Mission Operations Directorate (TMOD) at the Jet Propulsion Laboratory (JPL), which operates the DSN, has developed a road map that meets these challenges through the year 2010.

In addition to this significant growth in DSN ground capabilities, Douglas Abraham, *et al*., describe what will essentially be an extension of the DSN into space. Known as the Mars Network Project, this new initiative involves building a constellation of communication and navigation satellites in Mars orbit. When fully deployed, this constellation will improve communication and navigation performance at Mars by orders of magnitude and will play a key role in supporting Mars global reconnaissance, surface exploration, sample return missions, robotic outposts, and eventual human exploration. In the process, the increases in data rates and connectivity afforded by the Mars Network will ultimately enable people back on Earth to experience virtual presence at Mars — thus concluding the first step toward fulfilling NASA's vision of "virtual presence throughout the solar system."

Finally, Michael Klein and Mike Stewart describe the Goldstone-Apple Valley Radio Telescope (GAVRT) project and its use as an instrument for science education. Classrooms throughout the U.S. remotely operate the radio telescope through the Internet and the Science and Technology Center in Apple Valley. This project is being developed as a partnership between JPL TMOD and the Science and Technology Center (STC), a branch of the Lewis Center for Educational Research, Apple Valley, CA.

NASA's Deep-Space Telecommunications Road Map

TMOD TECHNOLOGY

C.D. Edwards, C.T. Stelzried, L. Swanson and J.R. Lesh

Introduction

NASA's Deep Space Network (DSN) road map for deep-space telecommunications through the year 2010 meets the challenges of future planetary missions. Key aspects of this road map are: (1) a move to efficient, standardized communications services; (2) development of an end-to-end flight/ground communications architecture and coordination of flight and ground technology developments; and (3) rapid infusion of Ka-band (32 GHz) and optical communications technologies into the DSN and into future spacecraft.

One of the primary goals identified within NASA's most recent strategic plan is "to establish a virtual presence throughout the solar system." The fidelity of this virtual presence will in large part be defined by the communications bandwidth that will link robotic spacecraft and the scientists, engineers, and public who interact with them from Earth. Consistent with this, the National Research Council recently identified "wideband, high-data rate communications over planetary distances" as one of six key technologies with the potential to "lower the cost and improve the performance of existing space activities and enable new ones."

Section II of this article describes the challenge TMOD faces as we move to an era of far more frequent launches. Section III presents TMOD's strategy for responding to this challenge, focusing on applying new developments in Ka-band and optical technology to provide extremely cost-effective growth in our deep-space communications capability. Finally, Section IV summarizes the results and recommendations of this strategy for the future of deep-space communications.

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II. Telecommunications Challenges

One of the most noteworthy dividends of a “faster, better, cheaper” NASA is the agency’s ability to launch more numerous new missions. The space program has successfully evolved in a few short years from an era of infrequent “flagship” missions to frequently launched missions and multimission programs such as Discovery, Mars, and Outer Planets. Based on a conservative forecast, TMOD anticipates a significant increase in the number of missions supported — from a current level of about 25 up to roughly 35 simultaneous missions in 5 years. A more aggressive forecast, based on the NASA Administrator’s goal of a launch every month, would result in over 50 simultaneous missions. This increasingly large mission set will challenge the capacity of the Deep Space Network.

In addition to the number, the types of missions NASA has planned will also stretch our deep-space communications capabilities. Outer-planet missions play a key role in NASA’s planetary road map, and because link performance scales inversely with the square of distance, receiving signals from Pluto or Neptune will be more than 100 times more difficult than from Mars — and 10 billion times more difficult than between a commercial geostationary satellite and the ground! Future missions will also be more data intensive. Compared with the current generation of flyby missions, long-duration orbiters and *in situ* investigations will incorporate high-bandwidth instruments such as multispectral imagers.

Based on today’s mission support scenario of three 8-hour tracking passes per week during cruise and daily 10-hour tracking passes during a prime mission phase (e.g., encounter), even the conservative future mission set mentioned above would lead to a 60 percent oversubscription of DSN antenna capacity by the year 2005.

How will JPL and NASA respond to this challenge? The answer is threefold. First, we will look at the telecommunication link from an end-to-end perspective, from the spacecraft instruments to the project scientists and engineers on the ground. TMOD will define the overall end-to-end architecture for deep-space communications and mission operations and create a coordinated technology development road map that responds to the needs of the anticipated future mission set. The model of this end-to-end architecture, shown in Figure 1, is a “solar system-wide area network,” providing seamless connectivity between scientists and their spacecraft instruments. Like the Internet, this network provides a layered architecture. There is a physical layer embodied by DSN assets on the ground and compatible radio systems on the spacecraft, a data-transport layer with Internet-like protocols designed to operate efficiently with the long round-trip propagation times and low signal levels of deep-space links, and an application layer to provide end-to-end information management across the flight/ground system. The application layer delivers needed software functionality on the ground and on the spacecraft in a migratable, evolvable fashion.

Second, TMOD will provide standardized, cost-effective, high-level services. In the past, missions have requested hours of DSN antenna time and dealt with their telemetry at the bit level. In the future, missions will request file transfers, analogous to the file transfer protocol (FTP) services used on the Internet, with robust space

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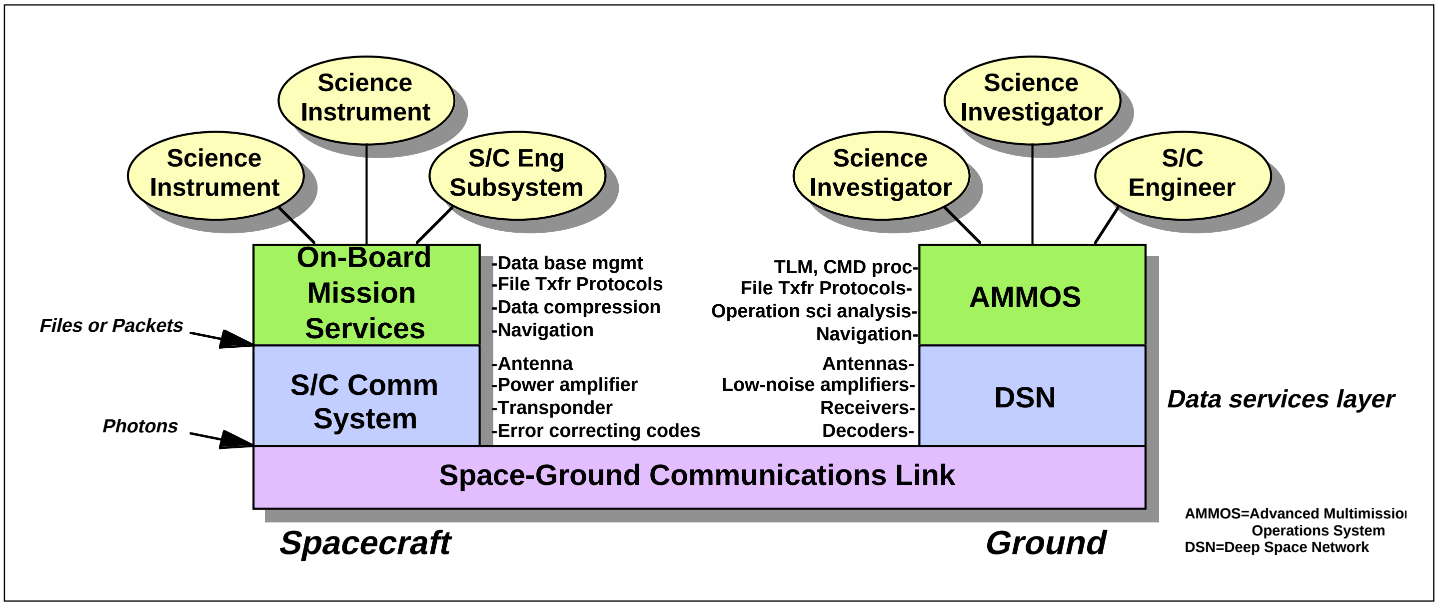
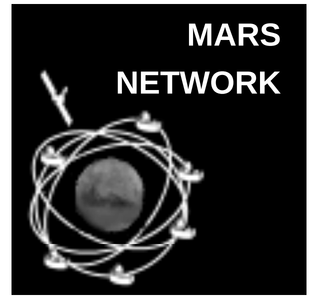
Figure 1. Layered flight/ground model of deep-space telecommunications and mission operations



Mars Network: Gateway to Mars and Beyond



DOUGLAS S. ABRAHAM, CHARLES D. EDWARDS, AND SHELDON N. ROSELL

Introduction

In cooperation with the Mars Surveyor Program, the Telecommunications and Mission Operations Directorate (TMOD) is embarking upon a bold, new initiative: the Mars Network Project. This project will support Mars global reconnaissance, surface exploration, sample return missions, robotic outposts, and eventual human exploration by:

- Developing a communications capability to provide a substantial increase in data rates and connectivity from Mars to Earth;
- Developing an *in-situ* navigation capability to enable more precise targeting and loca-tion information on approach and at Mars.

By developing the capability to provide increased data rates and connectivity, Mars Network also will enable greater information flow to the public for the purpose of engaging them in the Mars exploration adventure. In essence, Mars Network will be building a publicly accessible "gateway" to Mars.

The architecture under examination for enabling these capabilities consists of a constellation of microsatellites, or Microsats, and one or more relatively large Mars Areostationary Satellites, or MARSATs (Fig. 1). The Microsats will serve both as communication relays between Mars exploration elements (landers, rovers, balloons, airplanes, etc.) and the Earth and as naviga-tional aids for the exploration elements. MARSATs, on the other hand, will be much like the very high-bandwidth geostationary communications satellites in Earth orbit. These satellites orbit the Earth along its equatorial plane at the same rate as the Earth rotates. In so doing, they are always posi-tioned over the same region on the Earth. In the case of MARSAT, however, the satellite will orbit Mars in this fashion, not the Earth — hence, the name "areostationary" rather than "geostationary." For both Microsats and MARSATs, communication with the Mars exploration elements will occur using an internet protocol similar to what enables communications via Earth's Internet. Deployment of a prototype Microsat, tentatively scheduled for 2003, will be the first step in creating this Mars "Internet."

Why Do It?

I. Reduced Communications-Related Power, Volume, and Mass Requirements on Future Mars Exploration Elements.

NASA's Strategic Plan calls for, among other things, establishing "a virtual presence throughout the solar system." To do so, NASA not only has to deploy robotic probes across the solar system, but it also must ensure that reliable communication links exist between those probes and the Earth so that the data they send back can be adequately received. Since communications performance decreases with the square of the distance, establishing such links is not easy. A typical geostationary communications satellite orbits Earth at an altitude of about 40,000 km. But, a satellite transmitting back to the Earth from Mars is about 400 million km distant, making the communications 100,000,000 times more difficult. To overcome this difficulty, robotic probes at Mars and other locations around our solar system require significant power, antenna size, and associ-

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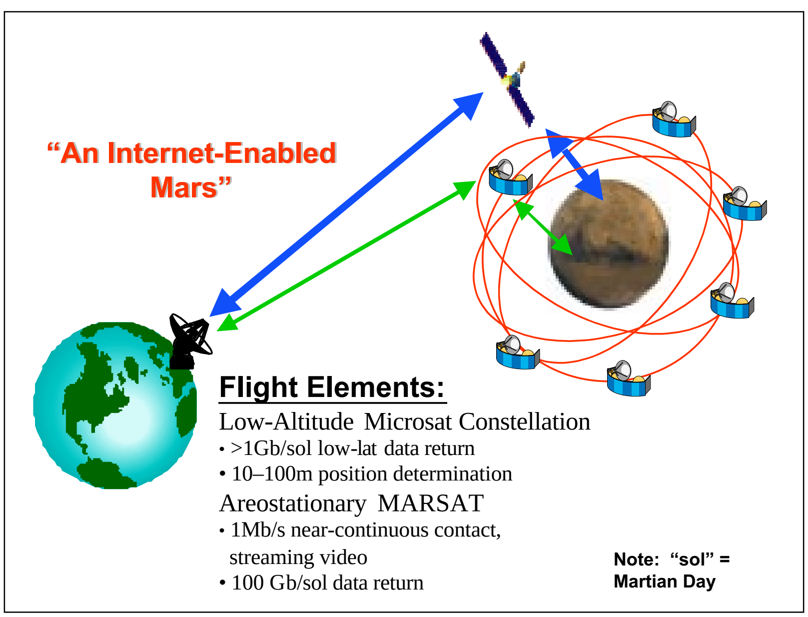

Figure 1. Mars Network Overview

MARS NETWORK CONTINUED FROM PAGE 3

ated mass. But, small landers, rovers, penetrators, etc., cannot accommodate these power, volume, and mass requirements. An *in situ* communications relay system, however, could greatly alleviate the burden of such requirements by serving as a "go between," allowing the exploration elements to communicate over much shorter distances. As shown in Figure 2, between 2003 and 2010, at least 18 distinct robotic exploration elements are slated for possible deployment at Mars, making Mars a logical first site for such an *in situ* communications relay system — hence, the Mars Network.

II. Enhanced Connectivity and Bandwidth for Increased Sense of Presence

While a few of the above robotic elements will still be built with their own direct-to-Earth communications capability, Mars Network, once fully deployed, will be able to substantially increase their communications rate and/or contact time. In so doing, Mars Network will increase the amount of data these elements return to Earth (Fig. 3). To the extent that a sense of presence can be better conveyed with greater quantities of data (such as video rather than snapshots, for instance), Mars Network's capability to increase data return from the exploration elements is particularly integral to establishing a "virtual presence" at Mars.

III. Improved Targeting and Location Information

Mars Network's Microsats will also work in concert to provide *in situ* navigation. Past Mars missions have relied on Deep Space Network (DSN) tracking from the Earth to target their approach and surface descent. This type of tracking typically provides position knowledge within an uncertainty of about 15 km when 125 km above the surface, and about 75 km when on the surface.

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Potential Mars Network Customers

- Micromission '03 Aircraft
- MSR '03 Lander and Rover
- MSR '03 Canister
- Beagle II
- MSR '05 Lander and Rover
- MSR '05 Canister
- Netlanders '05
- Micromission '05 Probe and/or Science Orbiter
- MSR '07 Lander and Rover
- MSR '07 Canister
- Micromission '07 Probe and/or Science Orbiter
- MSR '09 Lander and Rover
- MSR '09 Canister
- Micromission '09 Probe and/or Science Orbiter
- Robotic Outpost
- HEDS Piloted Missions

Figure 2. Mars Robotic Exploration Elements

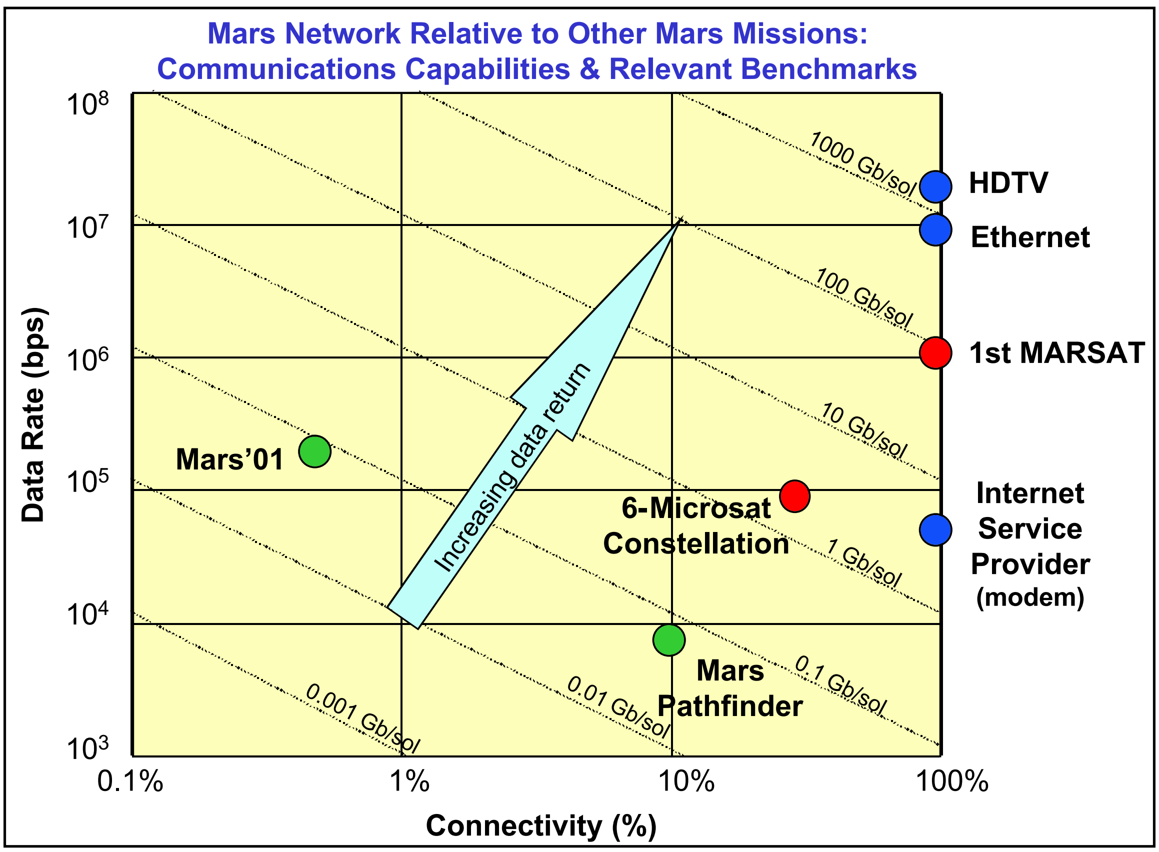

Figure 3. Mars Network's Capability to Increase Data Return

RADIO ASTRONOMY

The Goldstone/Apple Valley Radiotelescope

A Partnership in Science Education

Michael J. Klein and J. Michael Stewart

The Goldstone-Apple Valley Radio Telescope (GAVRT) is a unique classroom instrument for the study of radio astronomy, and is used for science education in schools across the country. The project is a joint venture developed and operated by the Jet Propulsion Laboratory (JPL) Telecommunications and Mission Operations Directorate (TMOD) and the Science and Technology Center (STC), a branch of the Lewis Center for Educational Research in Apple Valley, California.

This 34-meter diameter antenna was formerly a part of the Deep Space Network, which is operated for NASA by JPL. It is located within the Goldstone Deep Space Communication Complex in the Mojave desert north of Barstow, California. Designated DSS12, it was used for more than 30 years to navigate and communicate with robotic space probes launched to explore the solar system.

In 1994, as technically advanced tracking stations were being brought on-line at Goldstone, NASA decided to decommission DSS12 and remove it from the Network. Inquiries from the STC at Apple Valley led NASA to direct JPL to conduct a study evaluating the feasibility of converting the antenna to a remotely controlled radio telescope for use by middle school and high school students.

GAVRT Project Implementation

A team of engineers and scientists developed a technical design and implementation plan for the antenna, which was approved by JPL and NASA management. GAVRT was inaugurated in October 1996 when JPL and the Apple Valley Unified School District signed a Memorandum of Understanding at a ceremony attended by NASA Administrator Dan Goldin and Congressman Jerry Lewis, whose district includes both Apple Valley and Goldstone.

Technicians removed unneeded equipment from the antenna and installed a radio astronomy receiving system and new control cables. Software engineers adapted a developmental DSN remote-control subsystem designed to enable classrooms throughout the U.S. to operate the radio telescope through the Internet and "Mission Control" at the STC in Apple Valley. In May 1997, science classes in Detroit, Michigan, and the Apple Valley/High Desert area successfully conducted the project's first radio astronomy experiment.

The Jupiter Quest Curriculum

The GAVRT project is far more than a technical demonstration of remote access and control. The heart of the project is a performance-based science curriculum for middle school and high school teachers. This curriculum is being developed to meet state and national standards for science education. The project's intention is to assist teachers to fulfill these standards as they apply the GAVRT curriculum.

"Jupiter Quest," a hypothetical mission to Jupiter, is the first of several GAVRT curriculum elements. The project culminates with several radio astronomy observing sessions that will take place when classroom computers are connected to DSS 12 through Mission Control at the Science Center in Apple Valley. Students point the giant antenna, calibrate the instruments, and collect and analyze the data. They use their data to determine the temperature of Jupiter's atmosphere and study unpredictable variations in the intensity of the powerful donut-shaped radiation belt that encircles the giant planet (Fig. 1). Students from several schools scattered across the country team up to share data and produce their scientific reports. Finally, their results are authenticated at the STC and added to the data records at JPL (Fig. 2).

Because high-energy particles in Jupiter's radiation belt can damage the electronic components of spacecraft, the GAVRT data are also used by the professional community as they plan for future space missions to the Jovian system. Students learn first hand that science is a process, not simply a set of facts to be memorized.

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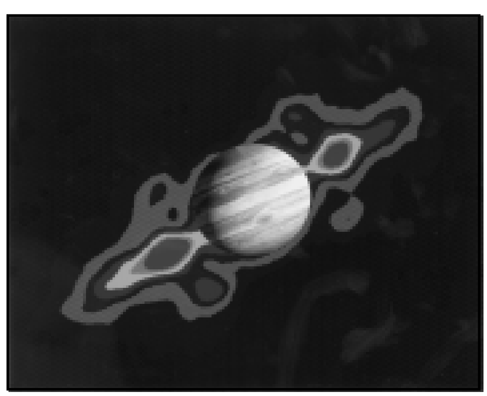

Figure 1. Jupiter's Radiation Belts: A Galileo image of Jupiter superimposed on a radio brightness map of the radiation belts observed at 1400 MHz by the Very Large Array (VLA) at the National Radio Astronomy Observatory

GAVRT CONTINUED FROM PAGE 5

The GAVRT Partnership

TMOD, the STC, and Allied Signal Technical Services Corp., which operates the Goldstone complex for JPL, were responsible for the project implementation. JPL technical training experts produced a set of training materials to introduce teachers to radio astronomy and the GAVRT radio telescope system. Scientists at JPL continue to contribute their time for training and consulting.

The project continues to evolve. New curriculum elements are being developed, and the number of participants in 1999 has grown to 18 schools located in 6 states. JPL maintains the telescope, develops system enhancements and provides scientific oversight and support. The Science and Technology branch of the Lewis Center in Apple Valley serves as Mission Control, develops and supports the science curriculum, and conducts teacher training workshops.

The GAVRT partnership strives to fulfill the project mission, " . . . to provide students and educators with curriculum vehicles that will promote science literacy, support a better understanding of the scientific community, and provide the opportunity to collect real-time data with sophisticated science equipment through distance learning."

For more information, visit the GAVRT web sites at:

http://www.avstc.org or

http://deepspace.jpl.nasa.gov/dsn/applevalley

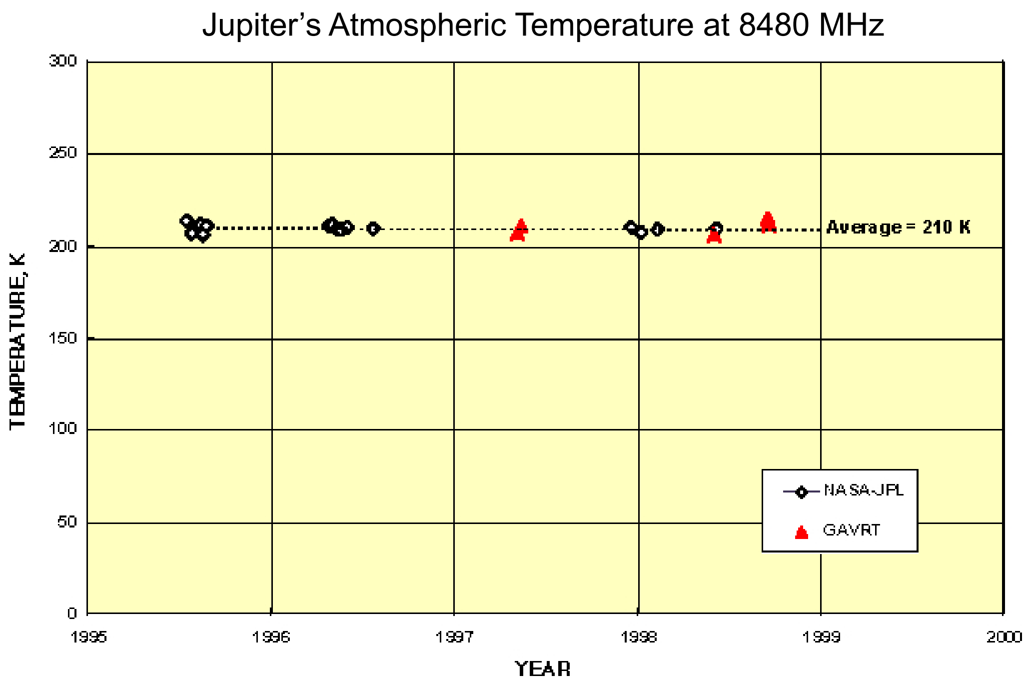

Figure 2. The temperature of Jupiter's atmosphere just above the water clouds where the temperature is a frigid 210K. These temperatures are derived from radio astronomy observations near 8480 MHz. Student results (GAVRT) are indicated by triangles

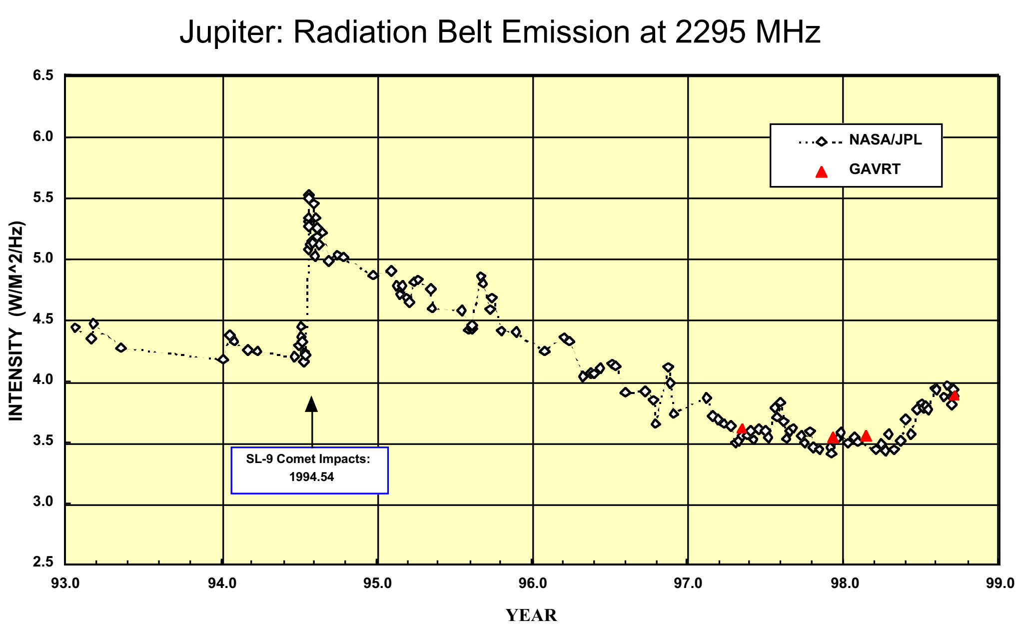

Figure 3. Jupiter's radiation-belt emission at radio frequencies has exhibited unpredictable variability for the past 30 years. This segment of the observational database shows the sudden "brightening" triggered by the impact of cometary fragments from Comet Shoemaker-Levy 9 (July 1994), as well as the good agreement between the student data (GAVRT) and the data from the NASA/JPL Jupiter Patrol

ROAD MAP CONTINUED FROM PAGE 2

communications protocols handling retransmissions. This system ensures that all data are successfully delivered to the project.

Third, a rapid infusion of new technology will be vital to meeting NASA's deep-space communications challenge. The quantity, quality, and cost of deep-space communications capabilities are highly dependent on the state of related technology; advances in component technology will offer opportunities for significant, cost-effective growth. In particular, Ka-band and optical communications technologies have the potential to provide an order of magnitude increase in performance by the year 2010.

III. Technology Road Map

Telecommunications Metrics

To speak quantitatively about communications performance, it will be useful to define some metrics. In the past, we have tended to think in terms of available antenna hours, a metric that is easy to understand. To increase this metric, new antennas can be built or their utilization increased by reducing setup times.

As NASA moves toward a service paradigm based on file transfers instead of antenna hours, it is helpful to characterize a second metric representing the data volume that can be downlinked into any given DSN antenna in a given pass length. Specifically, a "reference spacecraft" is defined at Jupiter distance: the spacecraft is normalized to have an RF output power of 10 W and an antenna effective diameter of 1.0 m (which, for a 50 percent efficient antenna, has a physical diameter of 1.4 m). This is characteristic of the types of communications systems that the mass-, power-, and volume-constrained missions of the future are baselining. Extended to the optical domain, a spacecraft system consisting of a 30-cm telescope aperture and a 3-W laser output can be postulated. This definition supports a quantitative discussion about the data rate that such a reference spacecraft could downlink into any given ground antenna (RF) or telescope optical.

Finally, assuming this single-aperture definition, a third metric may be defined as the aggregate data-rate capacity for the entire ground network—achieved by combining the downlink rates for all the antennas/telescopes in the DSN. This number corresponds to the aggregate bandwidth that the DSN could supply for an ensemble of reference spacecraft at Jupiter distances in different sky directions. In terms of this metric, today's DSN provides an aggregate capacity of 20 kbits per second (kb/s) at S-band (2.3 GHz), 240 kb/s at X-band (8.4 GHz), and no telemetry operational capability yet at Ka-band (32 GHz) or optical (1.06 um).

Baseline RF System Improvements

A number of planned improvements are expected to lead to significant increases in the DSN's current X-band telecommunications capability. These include the following:

1. DSN ground station automation. TMOD is initiating a comprehensive network upgrade that will modernize and simplify DSN subsystems. In addition to reducing operations costs, increased antenna utilization is expected, due to a reduction in the calibration time required for each tracking pass. Reducing calibration time is especially important with NASA's move toward shorter tracking passes. These network improvements are scheduled for completion in the 2001 time frame.

2. Improved X-band diplexing feed systems. A new, low-loss RF feed system design allows 2-way communications through a single diplexed RF feed, resulting in a substantial reduction in the operational system noise temperature.

3. Turbo codes. A new class of error-correcting codes is being developed, offering a 0.8-dB advantage over the current Reed-Solomon/convolutional (15,1/6) concatenated code. Implementation of turbo decoders in the DSN by 2003 is NASA's goal.

Ka-Band Communications Road Map

The DSN currently supports deep-space communications at S-band and X-band. While the baseline RF improvements mentioned above will increase DSN capacity, they are insufficient to meet the anticipated needs of the future mission set. We must either build additional S-/X-band antennas or move to higher communications frequencies.

The next frequency allocation for deep-space communications above X-band is Ka-band. Ka-band offers a roughly fourfold performance advantage over X-band for high-rate downlinks, due to the increased directivity of the downlink beam for shorter wavelengths. We make the following assumption: Future missions, starting in 2005, will utilize Ka-band to allow a 50 percent reduction in tracking time while achieving a factor-of-two increase in overall science data return.

A development road map supports the use of Ka-band in this time frame. Key aspects of the road map, shown in Figure 2, include the following:

1. Rapid deployment of Ka-band receiving capabilities in the DSN. DSS 13, DSN's research and development (R&D) antenna, has served as a test-bed for developing Ka-band ground technologies and currently supports Ka-band (Fig. 3). The first operational Ka-band capability is now on-line at DSS 25, a 34-m beam-waveguide (BWG) antenna at Goldstone's Deep Space Communications Complex. The road map calls for adding Ka-band to all five 34-m BWG antennas by 2003, followed by implementation on the three 34-m high-efficiency (HEF)

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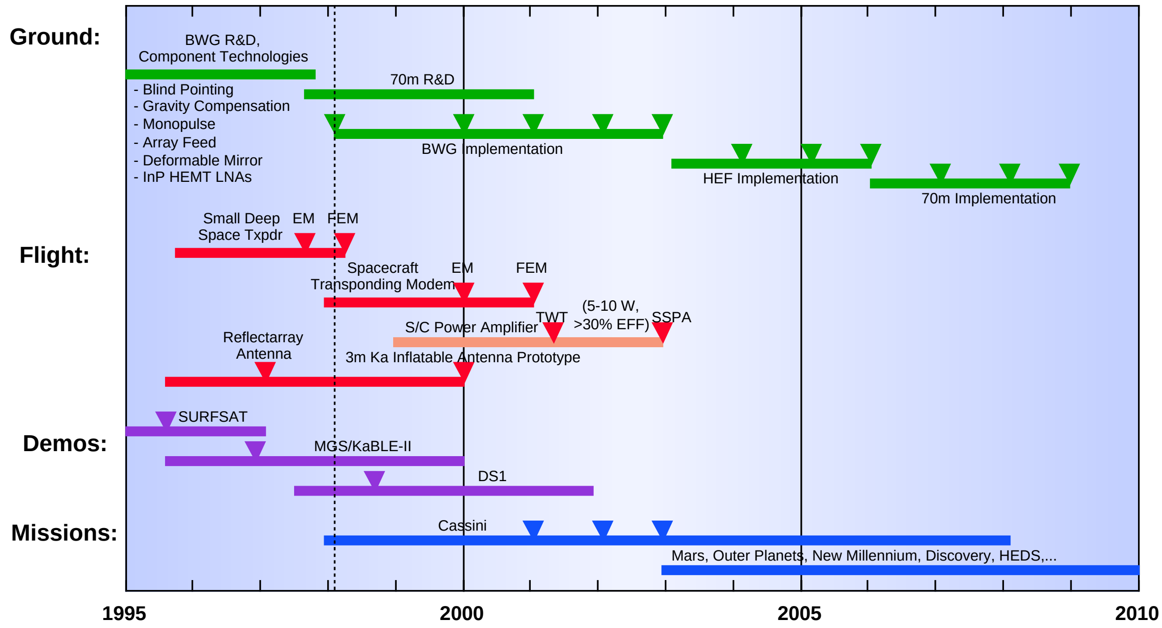
Figure 2. Ka-band deep-space telecommunications road map



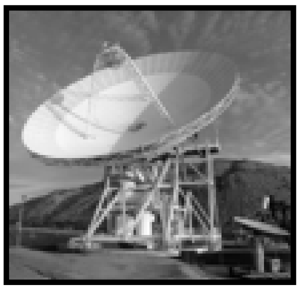


Figure 3. DSS 13, the DSN's 34-m research and development antenna

antennas by 2006, and the three 70-m antennas by 2009. Making 70-m antennas perform well at Ka-band is technically challenging — the primary antenna surfaces deform by a significant fraction of a wavelength with elevation angle. The TMOD Technology Program is pursuing two candidate technologies to compensate for these antenna deformations (Fig. 4). In one approach, a deformable mirror in front of the 70-m RF feed compensates for the wavefront distortion caused by the primary surface deformation. In the other, a cluster of seven feeds collects the defocused Ka-band signal and adaptively recombines it electronically.

2. Availability of efficient, low-cost, low-power, Ka-band flight components. Key elements of the spacecraft radio system include the transponder, the power amplifier, and the high-gain antenna, as discussed below.

The new Small Deep Space Transponder (SDST), developed by Motorola under contract to NASA, is flying on the New Millennium Deep Space 1 (DS1) mission, launched in 1998. This transponder provides both X-band and Ka-band downlink exciter options for the first time, in addition to its X-band uplink receiving capability. NASA's next-generation deep-space transponder is called the Spacecraft Transponding Modem (STM). Targeted for prototype delivery in 2001 and flight application starting in 2003, it will augment the SDST functionality with support of turbo codes, spacecraft timekeeping services, and frame-level interface with the flight computer — all in a smaller, lighter, lower power, and lower cost package.

Ka-band power amplifiers are currently a key missing element in the overall Ka-band system. While X-band solid-state power amplifiers (SSPAs) offer 30 percent DC-to-RF power efficiency and output power in the 5- to 10-W range, Ka-band SSPAs currently offer only about 10 to 15 percent power efficiency, with output power in the 1- to 3-W range. TMOD is establishing plans for the development of a 32-GHz traveling-wave tube amplifier (TWTA), with delivery of a prototype in 2000. Performance goals are 40 percent power efficiency, 10-W RF output, and 1.5-kg total mass.

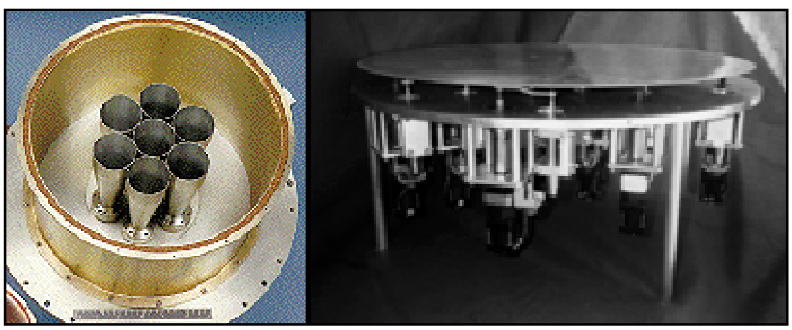


Figure 4. Deformable mirror (right) and seven-element array feed (left), two candidate technologies for achieving high aperture efficiency at 32 GHz on the DSN's 70-m antennas

Antennas vary from mission to mission, depending on specific telecommunications needs, spacecraft design issues, and launch vehicle constraints. Novel designs with lower mass or stowed volume are being investigated at Ka-band, including fixed and inflatable reflect-array antennas.

3. Flight demonstrations. Actual flight demonstrations are critical for validating Ka-band flight and ground components and assessing the increased effects of weather on the Ka-band link. The Mars Observer spacecraft carried the first deep-space experimental Ka-band downlink in 1992. Initial tests were consistent with anticipated link performance improvement, but the loss of the spacecraft limited the experience gained. Subsequently, in 1995, TMOD launched SURFSAT, a student-built payload attached to the upper stage of the RADARSAT launch vehicle, providing X-band, Ku-band (14 GHz), and Ka-band downlink test signals for validating ground-system technologies. More recently, in 1996, the Mars Global Surveyor spacecraft (Fig. 5) carried a second Ka-band flight experiment that included a 1-W Ka-band SSPA with 11 percent power efficiency and a dual-frequency X-/Ka-band high-gain antenna. The New Millennium DS1 mission is demonstrating Ka-band downlinks with the Small Deep Space Transponder and a 2.5-W, 15 percent efficient Ka-band SSPA. The flight experiments to date have validated DSN ground-system and spacecraft flight-system performance, as well as atmospheric effects at Ka-band.

Figure 5. The Mars Global Surveyor spacecraft, including the Ka-band Link Experiment (KaBLE-II)

4. Flight mission applications. Cassini is the first mission that is flying Ka-band as an operational part of its prime mission. Cassini uses Ka-band uplinks and downlinks, not for telemetry but rather for high-precision radio science experiments. A single Goldstone 34-m BWG antenna, DSS 25, supports these Ka-band links, providing a benchmark for ground-station performance and valuable experience in working at Ka-band. A wide array of missions in the 2003-and-beyond time frame are now looking at Ka-band as an option for their mission designs. Potential users include missions in the Mars Surveyor Program, the Outer Planets Program (including Europa Orbiter, Pluto Express, and Solar Probe), the new Millennium Program, and yet-to-be-named missions in the Discovery Program. TMOD will be working to cooperatively examine the end-to-end telecommunications link issues and the potential benefits of Ka-band for these missions.

Optical Communications Road Map

Looking beyond Ka-band, optical technology holds the promise of even higher telecommunications performance, with its greatly increased directivity of the spacecraft's laser signal toward Earth (A 1-m spacecraft RF antenna generates a diffraction-limited beamwidth of about 30 mrad at X-band and 10 mrad at Ka-band, a 10-cm telescope generates an optical beamwidth of 10 urad or less). Though in its early stages, the development of optical communications for deep space applications has already accomplished several important milestones. In 1992, the Galileo OPtical EXperiment (GOPEX) successfully demonstrated transmission of ground-based laser signals to the Galileo spacecraft. In 1995, JPL and Japan's Communications Research Laboratory collaborated to demonstrate bidirectional optical communications at rates of up to 1 Mb/s between JPL's Table Mountain Facility (TMF), located in Southern California, and the Japanese ETS VI spacecraft (Fig. 6). This study was known as the Ground-to-Orbit Lasercom Demonstration (GOLD). On the flight side, NASA's Cross Enterprise Technology Program has sponsored the development at JPL of an Optical Communications Demonstrator (OCD), shown in Figure 7. The OCD is a prototype optical communications terminal applicable to Gb/s near-Earth missions as well as lower rate deep-space missions.

As with the RF domain, TMOD has established a coordinated flight/ground road map of technology development leading to a deep-space optical communications capability, as shown in Figure 8 and discussed below.

1. Deployment of optical ground stations. In 1998, TMOD initiated the development of an Optical Communications Telescope Laboratory (OCTL), a 1-m optical telescope situated at JPL's Table Mountain Facility. Slated for first light in late 2000, OCTL will play a role for optical communications very similar to that of DSS 13, the DSN's 34-m

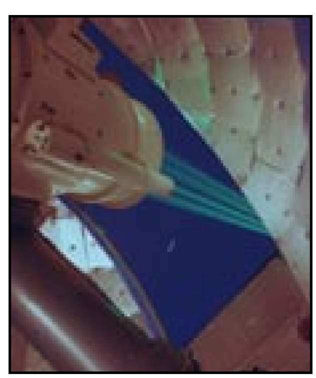


Figure 6. Multi-beam laser uplink from Table Mountain's 0.6-m telescope to the ETS-VI spacecraft during the Ground to Orbit Lasercom Demo (GOLD)

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R&D antenna, which is used in the development of the DSN's emerging Ka-band capabilities. OCTL will support early demonstrations of optical communications and provide a test-bed for component-level developments—ultimately needed for operational deep-space use of the technology. OCTL will support high slew rates, allowing its use in near-term demonstrations from low-Earth-orbiting platforms. In the longer term, operational deep-space optical downlinks will require significantly larger apertures.

TMOD's roadmap calls for the establishment of a network of 10-m optical ground stations for deep-space support in the latter part of the next decade, timed to the need dates of the first deep-space optical user missions. These non-diffraction-limited ground stations, known as "photon-buckets," have relaxed surface tolerances, and hence lower costs, relative to 10-m astronomical telescopes. Each 10-m photon-bucket station would include a 1-m uplink telescope for providing uplink communications signals or uplink reference beacons for accurate downlink spacecraft beam-pointing. Multiple ground stations would be employed to provide site diversity for mitigating the effects of weather outages.

2. Development of optical flight components. The OCD prototype terminal provides a basis for developing efficient deep-space and near-Earth flight terminals. During the latter half of FY97, the development of a 30-cm diameter flight transceiver using a 3-W Nd:YAG laser transmitter was started under the X2000 Delivery 1 program. Targeted for missions like Europa Orbiter, the subsystem objectives included downlink data transmission at rates up to 400 kbps (100 kbps during high-background daytime conditions), uplink reception at 2 kbps, the capability to do two-way ranging, and reception of laser altimeter return echoes at 532-nm wavelength. Unfortunately, shifts in X2000 program priorities and budget resulted in a smaller terminal development as part of the X2000 Delivery 2 program element. This transceiver is modeled after the Advanced Communications LAser and IMaging (ACLAIM) breadboard, which was funded by the next-generation spacecraft technology program.

The flight engineering transceiver model being developed under Delivery 2 uses a 10-cm telescope and 1-W laser, and will provide dual-use functionality, doubling as a science imaging camera. The unit will be capable of sending up to 40 kbps from 2 AU with a 4-kg, 14-W terminal. Completion of the engineering model is scheduled for December 2003. Although an important step for advancing optical communications flight terminal technology, extensions to

Figure 7. The optical communications demonstrator

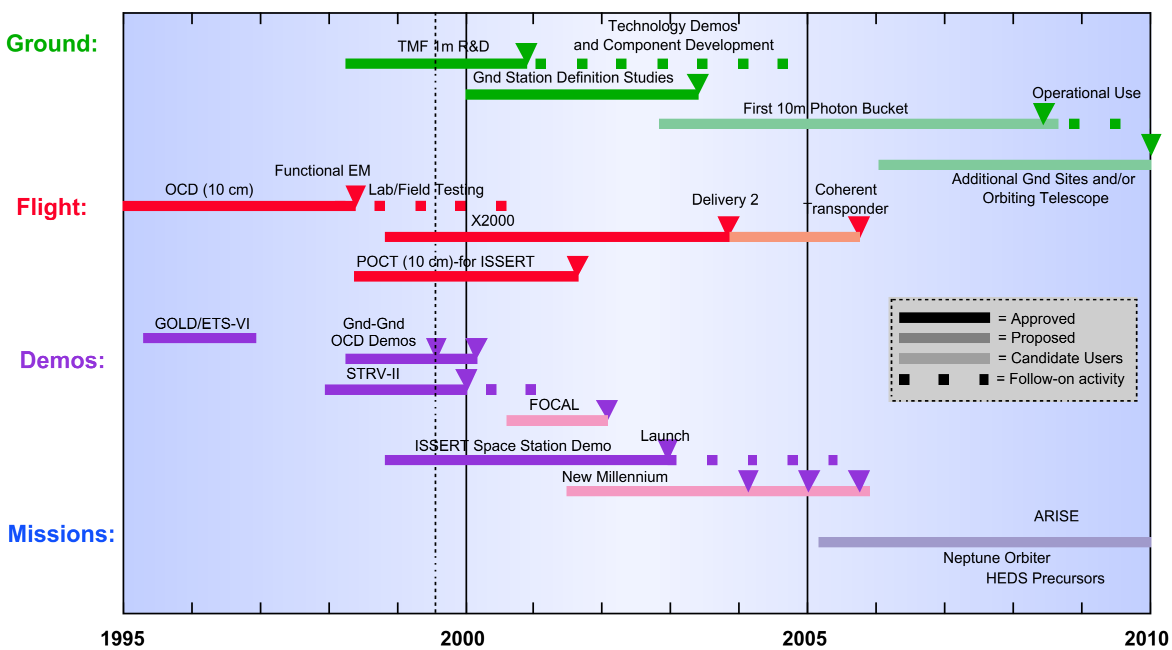

Figure 8. Optical deep-space telecommunications road map

larger (e.g., 30-cm diameter) terminals will still be required to meet the needs of future outer-planet exploration missions.

3. Flight demonstrations. The GOPEX and GOLD demonstrations mentioned above were targeted at understanding the fundamental properties of optical communications, specifically the ability to blind-point an uplink beam to a spacecraft using only navigation predicts (GOPEX) and validating multi-beam techniques to mitigate the effects of uplink beacon beam scintillation (GOLD). Demonstration of NASA-developed flight terminal technology has only been done in ground-to-ground tests between the Table Mountain Facility and Strawberry Peak. This series of ongoing 46 km horizontal path experimental trials, funded jointly by the TMOD Technology and TAP Cross-Enterprise Technology Programs, is being done to more fully understand the atmospheric effects on optical communications terminal performance, with particular emphasis on how they impact the spatial acquisition and tracking subsystem. Convincing flight project mission planners that the technology is sufficiently mature will require actual space flight demonstrations.

In 1998, a proposal from JPL for a space-to-ground demonstration was selected for funding by the International Space Station Engineering Research and Technology (ISSERT) program office at Johnson Space Center. The demonstration proposes a flight-qualified 10-cm diameter variant of the OCD design called POCT (for Proto-flight Optical Communications Terminal), operating with a 200-mW, 1.55-um laser transmitter, to demonstrate the transfer of up to 2.5 Gbps from the International Space Station to the OCTL ground R&D facility. The flight terminal is manifested and scheduled for launch in February 2003 on the Space Shuttle-based Express Pallet (flight UF3). After demonstrating high-data rate transfer and collecting adequate data to verify link performance prediction models using test data, the terminal may be made available to other flight experimenters for enhanced space-to-ground data dump. The development of the flight terminal could be completed as early as the first part of FY01, and a possible precursor demonstration (called FOCAL, for Free-space Optical Communications Assessment Link) from the Space Shuttle to ground is being considered. Using OCTL to conduct a demonstration with a DoD-funded flight terminal on the Space Technology Research Vehicle II (STRV II) is also being considered.

Even more convincing to space science mission planners would be a demonstration of optical communications from deep space. The combined optical comm/imager terminal being developed under the X2000 Delivery 2 program could be available for flight demonstration as early as 2004. As that date approaches, possible flights on one of the Space Technology (formerly New Millennium) program missions will be considered.

4. Flight mission applications. With flight demonstrations being conducted in the early-to-mid 2000's, the first mission applications of optical communication capabilities will likely be in the latter half of the next decade and beyond. Planning for a mission set that far in the future is somewhat high-risk. However, there are some proposed missions that could significantly benefit from this technology, described below by mission class.

The first class includes the really far outer-planet missions where distance-squared propagation losses are extremely large for lower frequency transmissions. One representative member of this class is Neptune Orbiter. The absolute data rates won't be that high (10's of kbps), but the distance-squared-times-data-rate-product will be very large. Without the higher bandwidths enabled by optical communications, the scientific objectives will be significantly constrained.

The second class involves the very high data rate astronomical observatories like the ARISE mission and possibly the Next Generation Space Telescope. ARISE, planned for launch in 2008, calls for data rates as high as 8 Gbps to relay the signals from its 25-m RF antenna to the Earth for interferometric combination with Earth-received signals. Optical communications at such high rates can be easily achieved, and the resulting transmitted signals are not subject to the severe spectral limitations imposed on RF carriers.

The third class consists of moderately high data rates from intermediate distances. Such missions would include future transmission links needed to support proposed robotic and human outposts on Mars.

The reason that higher data rates can be achieved with optical communications is that the narrow beam divergences at optical frequencies produce very large theoretical gains relative to RF communications. For example, the theoretical gain relative to X-band is about 75 dB. System designers can use this gain to achieve much higher data rates, significantly smaller communications subsystems, or a combination of both.

Conclusion

The impact of these new technologies can be quantified by revisiting the telecommunications metrics defined on page 8. First is the simple metric for available DSN tracking time and the anticipated 60 percent DSN over-subscription, based on a projection of the needs of the rapidly

CONTINUED ON NEXT PAGE

ROAD MAP CONTINUED FROM PAGE 11

expanding mission set and using current operations concepts. The Ka-band road map, coupled with planned ground-system automation (to increase antenna availability) provides a cost-effective path to satisfy this demand in the near term, while simultaneously providing increased science data return to future missions. With network-wide Ka-band support on all 34-m BWG antennas by 2003 and the availability of efficient, low-mass, low-cost, Ka-band flight components in this same time frame, Ka-band will be a very viable option for missions in the 2003 to 2005 interval and beyond. The roughly fourfold performance advantage of Ka-band relative to X-band will enable future missions to adopt a new operations concept that requires less DSN tracking time by a factor of two, but still provides roughly a factor of two more data volume. In addition, implementation of highly automated DSN ground systems in this time frame will increase available antenna hours by reducing precalibration and postcalibration time. A revised DSN loading study, based on the assumption that NASA missions starting in 2005 will use Ka-band to reduce their tracking requirements (to one 5-hour pass per week in cruise phase and one 5-hour pass per day in the prime science phase, which still provides an overall increase in data volume return), shows that the anticipated mission set can be supported quite well using existing DSN assets outfitted with new Ka-band electronics.

Regarding the second metric, the actual data volume that can be obtained in a 5-hour tracking pass is of interest to future mission designers. Link analyses for X-band, Ka-band, and optical links using various ground assets exhibit the performance gains possible by moving to higher frequencies, as shown in Table 1. (These links' performance, based on the analysis and DSN present and future performance estimates, represent theoretical capabilities and do not include additional link margins or the allocation of power to residual carriers or ranging channels. See the table notes for detailed assumptions. Use these numbers as a guide to the relative performance of different configurations.) Several observations can be made: First, these numbers confirm that a 34-m antenna Ka-band link is roughly comparable to a 70-m antenna X-band link and nearly four times higher than a 34-m antenna X-band link. Second, if the development of adaptive Ka-band feed systems succeeds on the 70-m antennas, even higher performance is possible. In fact, the Ka-band 70-m antenna link provides performance nearly equivalent to the optical 10-m telescope link for the spacecraft configurations considered here.

The third metric, aggregate ground network capacity for deep-space communications, demonstrates (at the highest level) how these technology developments will lead to a dramatic increase in the bandwidth available for supporting fleets of robotic and, ultimately, piloted missions in the new millennium. Figure 9 shows the growth of this aggregate communications data-rate capacity metric at S-band, X-band, Ka-band, and optical frequencies between now and 2010 based on the technology road maps presented here. Several

Table 1: Data return (Mbytes) for a 5-hour tracking pass

	X-Band		Ka-Band		Optical	
Planet	34 m	70 m	34 m	70 m	1 m	10 m
Mars	182.6	727.5	659.6	1772.1	29.5	2151.3
Jupiter	42.2	168.2	152.5	409.6	6.8	497.3
Saturn	12.5	49.9	45.2	121.4	2.0	147.4
Pluto	0.7	2.9	2.6	7.1	0.1	8.4

Notes:
RF cases referenced to 1m diameter effective s/c antenna, 10 W RF radiated power;
Optical cases referenced to 30 cm s/c telescope, 3 W optical transmitted power, λ=1.06 µm;
RF values averaged over complexes; optical assumes Goldstone;
RF cases assume 6K CCR HEMT LNA systems;
Optical cases averaged over Sun-Earth-Probe (SEP) angle;
Optical performance varies w/SEP angle; 10 m: ±50% (1m: ±5%) for SEP=180 deg to 10 deg;
All cases referenced to data rate at 30 deg elevation angle;
RF links assume 90% availability; optical assumes 70%; data volume deweighted by availability;
No additional link margin included.

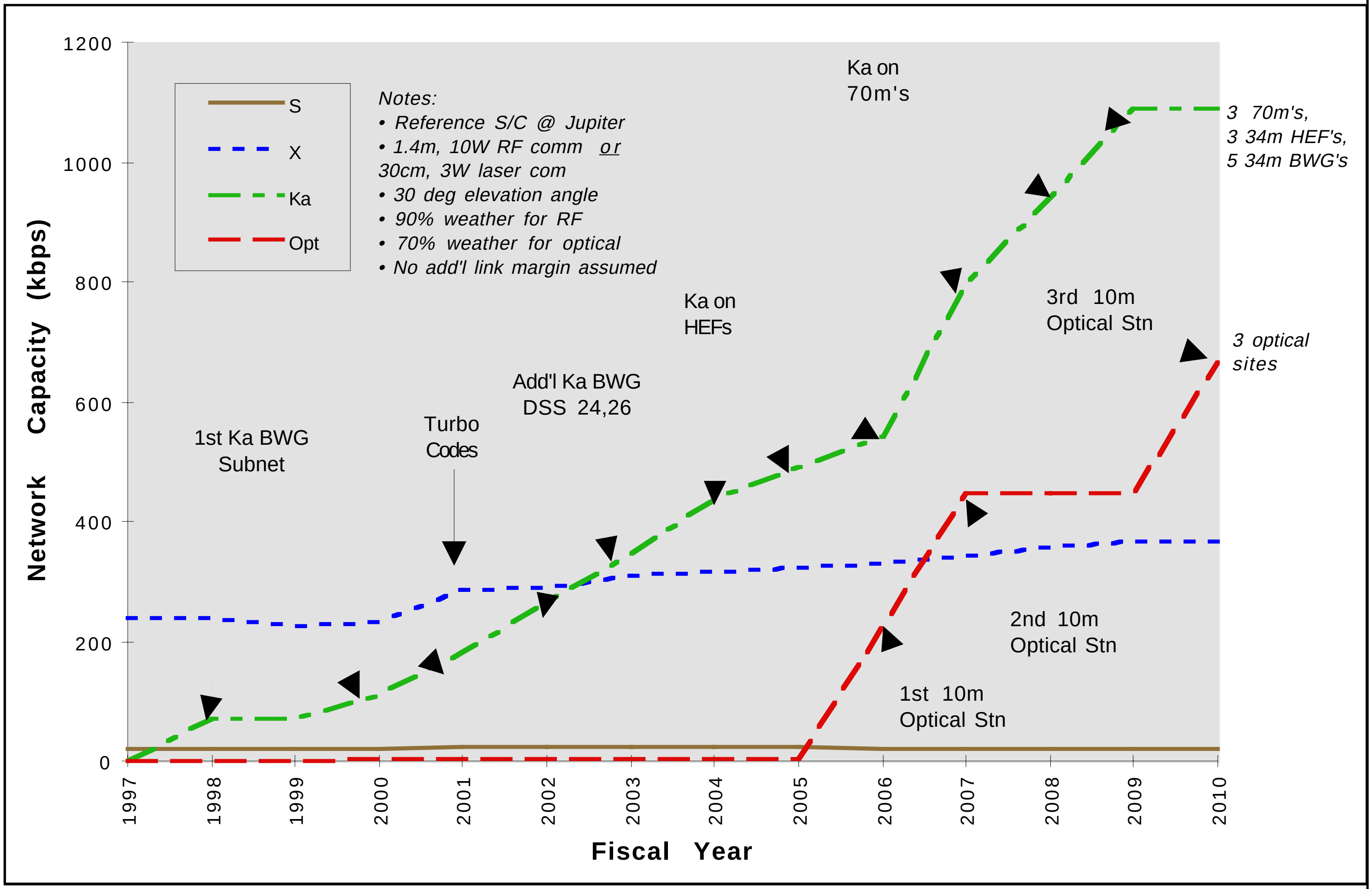

Figure 9. Projected growth in NASA's deep-space communications capability based on new RF and optical communications technologies

observations can be made: the use of new turbo codes, as well as planned improvements in our current feed systems, will lead to continuous incremental growth of our existing X-band capability; the proposed Ka-band implementations provide substantial growth — the Ka-band capability of just the five BWG antennas will outperform the entire DSN at X-band (with the addition of Ka-band to the HEF and 70-m antennas, the resulting Ka-band capability will be more than four times our current X-band capacity); optical communications technology provides a long-range path to future growth — the first optical 10-m station alone will offer roughly the performance of today's entire DSN capacity.

In conclusion, new RF and optical technologies are poised to provide breakthrough increases in deep-space telecommunications capacity, allowing NASA to meet the needs of a growing and increasingly challenging mission set while offering increased data return to individual missions. In the near term, the addition of Ka-band capabilities to existing DSN antennas is an extremely cost-effective way to increase capacity. In the longer term, optical communications appears to be a promising path for future growth. Achieving this growth will require a coordinated approach toward the development of flight and ground technologies. Milestones for the road maps include developing efficient Ka-band spacecraft amplifiers, demonstrating the potential performance of the 70-m antennas at Ka-band, and establishing one or more near-term optical flight demonstrations. The road map presented here provides a cost-effective path to significant improvements in NASA's deep-space communications capability, moving toward NASA's ultimate goal of establishing a virtual presence throughout the solar system.

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MARS NETWORK CONTINUED FROM PAGE 4

For many future targeted robotic and piloted missions, this level of position uncertainty is unacceptable. Suppose, for instance, one is trying to land a mission near a previously stashed cache of consumables; 75 km is a long trek from the landing site. On the other hand, using combined 2-way ranging, three Mars Network Microsats (or 2 Microsats and a properly equipped surface element) will be able to reduce position uncertainty at 125 km above the surface to less than 1 km. On the surface, position uncertainty will decrease to within 10 to 100 meters! With rovers, sample return canisters, balloons, and other mobile exploration elements able to accurately determine their position, Mars Network will enable a whole new level of autonomous robotic and, eventually, safe piloted exploration.

Mars Network: The Elements

The Microsats

As noted in the introduction, Mars Network will consist of a constellation of Microsats and one or more relatively large MARSATs. The Microsats will utilize a generic micro-spacecraft bus being developed by the Mars Surveyor Program (MSP) for a series of small, inexpensive science orbiter and probe micromissions. The main design driver for this bus is the need to minimize cost. MSP is focussing on minimizing cost in two arenas: developing the spacecraft itself and launching it. To reduce the cost to develop the spacecraft, MSP is designing the bus to be "single-string" (i.e., without redundant subsystem components), with a 3- to 5-year design life. To reduce the cost to launch the spacecraft, MSP is designing the bus for launch as a small auxiliary payload on an Ariane 5. As part of the international collaboration occurring to support Mars exploration, the French space agency, CNES, will pay for at least the first couple of such auxiliary payload launches, making them "free" to NASA. The prototype Mars Network Microsat tentatively scheduled for deployment in '03 will use the MSP bus and will be one of those auxiliary payloads.

To fit into the small banana-shaped volume available on the Ariane 5, the Microsat will, as its name suggests, be very small. Its dimensions will be 250 cm by 60 cm by 80 cm, and its mass, with a full propellant load, will only be around 220 kg — about the weight of two large men. The propellant load itself will comprise about 140 kg of that and will be just enough to enable the Microsat to move from an Earth geosynchronous transfer orbit to an Earth-lunar phasing trajectory, perform an Earth-lunar gravity assist, inject into an elliptical orbit around Mars, aerobrake down to an altitude of 800 km, circularize the orbit, and maintain attitude control during operations.

Within the stringent mass and volume constraints just discussed, the prototype Microsat must squeeze in both a deep space transponder and high-gain antenna for communicating with the Earth, and a transceiver and one or more antennas for communicating with the Mars exploration elements. The radio system for communicating with the Earth will operate at X-band (8.4 GHz), supporting a high-capacity, long-haul data link. Subsequent Microsats will carry an even higher frequency, soon-to-be-developed Ka-band radio system to enable a higher capacity, long-haul data link. On the deep-space link back to Earth, the Microsat will employ a pointed, high-gain dish antenna suitable for gathering and emitting the short wavelength X- or Ka-band signals back to Earth (Fig. 4).

For the *in situ* communication link with the Mars exploration elements, however, both the prototype Microsat and subsequent Microsats will use a lower frequency UHF transceiver and omni-directional antenna (or multiple directional antennas). This lower frequency, longer wavelength band will be used for the *in situ* communications due to the less stringent antenna pointing requirements associated with it. With less strin-

Figure 4. Artist's concept of the MICROSAT with high-gain antenna deployed

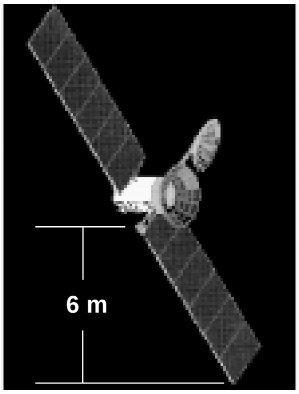

Figure 5. Artist's concept of the MARSAT

gent antenna pointing requirements, the Microsat will be able to communicate with exploration elements at a variety of locations without having to point at each one sequentially.

The MARSATs

The MARSATs comprise the second part of the Mars Network. As noted in the introduction, the MARSATs will be much like the very high-bandwidth geostationary communications satellites in Earth orbit, except that they will be in a similar type of orbit around Mars. While the MARSATs may not serve any specific navigation function, they will provide a breakthrough increase in connectivity and data rate. This increase will come from two factors, respectively: the MARSAT's orbit and the type of telecommunications equipment it will use for both the *in situ* and long-haul communications links. As discussed earlier, the MARSATs will be in areostationary orbits that will keep them continuously in view of and in contact with the same hemisphere of Mars (except when interrupted by infrequent eclipses). This continuous contact time potentially enables the collection of huge volumes of data from the exploration elements.

The second factor, the type of telecommunications equipment, drives MARSAT's high data rate. MARSAT will be using a high-power, very high-frequency Ka-band transceiver and a large, high-gain, dish antenna to provide a high-capacity, long-haul data link to the Earth. For *in situ* communication with the Mars exploration elements, MARSAT will employ a high-power, high-frequency X-band transceiver and pointable, high-gain, dish antenna — as well as one or more smaller spot antennas. To the extent that the exploration elements are also equipped with X-band transmitters or transceivers, the first MARSAT's equipment will enable data rates of up to 1 megabit per second, or fast enough to allow streaming video from the exploration elements. Combined with the continuous contact time associated with the areostationary orbit, these data rates will enable orders of magnitude more data return than with the Microsats alone.

Because MARSAT's high-power transceivers and high-gain antennas entail large amounts of power, volume, and mass, and because achieving an areostationary orbit requires very large propulsive maneuvers, the MARSAT itself will necessarily be fairly large. Current MARSAT point designs indicate kilowatt-level power requirements, with the solar array wing dimensions needed to provide such power on the order of 6 m by 2 m per wing (Fig. 5). MARSAT's mass in these designs ranges between 800 and 1000 kg. These power, volume, and mass characteristics necessarily drive the MARSAT toward being a primary payload on a Delta-class launch vehicle. Hence, the development and launch costs for MARSAT will be significantly greater than those associated with the Microsats. Fortunately, only two to three MARSATs will be needed to provide Mars with near-continuous, high data rate, global coverage. And, each MARSAT will be large enough to accommodate subsystem and component redundancy sufficient to achieve a minimum operational life of 7 years — thereby reducing the frequency with which such satellites will need to be replaced. The first of these MARSATs is tentatively planned for launch in 2007.

Mars Network Evolution

The Microsats

With the first Microsat deployment potentially occurring in 2003, and one equatorial and one polar Microsat planned for launch during each subsequent opportunity (which occurs about every two years given the relative motions of the Earth and Mars), the Mars Network Project is targeting having an operational, *in situ* navigation-capable, three-satellite constellation by late 2005. A fully operational six-satellite constellation is targeted for late 2009. The six-satellite constellation will provide for a robust communication and navigation infrastructure at Mars, with frequent contact opportunities.

The MARSATs

By adding a MARSAT to this constellation in 2007 and a second, higher capacity one in late 2009, the Mars Network Project plans to be on a path to providing a quantum leap in communications capability for exploration elements designed to capture near-continuous video. Some of these exploration elements might include robotic sample return missions, robotic outposts, and piloted Mars missions for which over-the-horizon communications, high-fidelity sustained virtual presence, and high-rate two-way HDTV may be particularly important.

A Mars Internet

As the number of Mars exploration elements and Network constellation elements increase, so will the complexities of trying to coordinate the communications occurring between them. The

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problem is not too dissimilar from that encountered on the Earth in the 1980s when computer users at disparate locations across the globe all began trying to get their various brands of computers to communicate with one another in some standard way. The solution to that problem was the Internet and, more specifically, the internet protocol (IP) computers began using when linking to each other through phone lines. With this analogy in mind, Mars Network is working with the Internet community to establish a Mars Internet, with an IP-like protocol that will facilitate file-level communications between exploration and constellation elements and be robust enough to contend with long round-trip light times and noisy, intermittent, power-constrained deep space links. To the extent that these efforts succeed at Mars, one can imagine Mars becoming the first of many gateways on an Interplanetary Internet — an internet enabling virtual presence throughout the solar system.

Current Status

The Mars Network Project is currently working three fronts:

- Detailed design of the prototype Microsat.
- Design of the overall Mars Network architecture.
- Creation of a public, virtual presence interface for Mars Network — a "Mars Exploration Gateway"

Detailed design of the prototype Microsat is currently focused on the design of the *in situ* communications payload, the concept for how the payload will be operated once in Mars orbit, and specification of the requirements that the payload and its operation levy on MSP's design of the micro-spacecraft bus. JPL has recently released an RFP for development of the bus.

Design of the overall Mars Network architecture is currently focused on determination of Mars exploration element communications and navigation requirements as a function of time. The Mars Network Project will then plan accordingly for deployment of, and capability upgrades to, the Microsats and MARSATs. Examples of architecture design considerations inherent to this planning include such things as the appropriate orbits for each of the Network elements, the number of simultaneous users and frequency channels for the transceivers, hailing protocols between Mars Network and exploration elements, the need for satellite cross-links, and the concept for how the constellation will be operated and maintained.

Whatever its ultimate architecture, Mars Network will essentially be a "pipeline" through which the other Mars exploration elements can return their data to Earth. The increased bandwidth and connectivity associated with this "pipeline" will enable greater information flow to the public for the purpose of engaging them in the Mars exploration adventure. To this end, the Mars Network Project is coordinating with the other Mars projects, the Space and Earth Sciences Outreach and Education Office, the JPL Educational Affairs Office, and the Commercial Technology Programs Office to create an interactive, internet-based "Mars Exploration Gateway" — a virtual-presence interface with the Mars Network for the public. In so doing, Mars Network is exploring partnerships with industry, academia, and others to enhance the quality and accessibility of this interface. Mars Network's ultimate goal is the creation of a virtual gateway through which the average individual can pass into and explore the Mars frontier — a first stop on the Interplanetary Internet.

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